Search for a Higgs boson decaying into $\gamma^*\gamma \to \ell\ell\gamma$ with low dilepton mass in pp collisions at $\sqrt{s} = 8$ TeV

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**Abstract**

A search is described for a Higgs boson decaying into two photons, one of which has an internal conversion to a muon or an electron pair ($\ell\ell\gamma$). The analysis is performed using proton–proton collision data recorded with the CMS detector at the LHC at a centre-of-mass energy of 8 TeV, corresponding to an integrated luminosity of 19.7 fb$^{-1}$. The events selected have an opposite-sign muon or electron pair and a high transverse momentum photon. No excess above background has been found in the three-body invariant mass range $120 < m_{\ell\ell\gamma} < 150$ GeV, and limits have been derived for the Higgs boson production cross section times branching fraction for the decay $H \to \gamma^*\gamma \to \ell\ell\gamma$, where the dilepton invariant mass is less than 20 GeV. For a Higgs boson with $m_H = 125$ GeV, a 95% confidence level (CL) exclusion observed (expected) limit is $6.7\, (5.9\, +2.8\, )$ times the standard model prediction. Additionally, an upper limit at 95% CL on the branching fraction of $H \to (\Upsilon/\phi)\gamma$ for the 125 GeV Higgs boson is set at $1.5 \times 10^{-2}$.

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1. Introduction

The rare decay into the $\ell\ell\gamma$ final state of the Higgs boson is a rich source of information that can enhance our understanding of its basic properties and probe novel couplings predicted by extensions of the standard model (SM) of particle physics. As illustrated in Fig. 1, this decay in SM has contributions from loop-induced $H \to \gamma^*\gamma$ and $H \to Z\gamma$ diagrams (a, b, c), tree-level process $H \to \ell\ell$ with final-state radiation (d), and higher-order processes, known as box diagrams (e, f, g) [1–4]. Other contributions include $H \to V(q\bar{q})\gamma \to \ell\ell\gamma$, shown in Fig. 2, where $V$ denotes a vector meson ($J/\psi$ or $\Upsilon$) that decays to $\ell\ell$ [5–7]. The Higgs boson branching fraction to $\ell\ell\gamma$ is dominated by the $H \to \gamma^*\gamma$ and $H \to Z\gamma$ modes, while the contribution from the box diagrams is negligible [1]. In the muon channel, when the dilepton invariant mass, $m_{\ell\ell}$, is greater than 100 GeV, final-state radiation in $H \to \mu\mu$ starts to dominate [8]. In the three-body decay, $H \to \ell\ell\gamma$, it is possible to investigate non-SM couplings by examining the angular distributions, and forward–backward asymmetry variables reconstructed from the $\ell\ell\gamma$ final state [8,9].

The expected rates of the $H \to (Z/\gamma^*)\gamma \to \ell\ell\gamma$ processes compared to the rate of $H \to \gamma\gamma$ decay, for a Higgs boson with mass $m_H = 125$ GeV, are [10,11]:

$$\frac{\Gamma(H \to \gamma^*\gamma \to e\ell\gamma)}{\Gamma(H \to \gamma\gamma)} \sim 3.5\%,$$
$$\frac{\Gamma(H \to \gamma^*\gamma \to \mu\ell\gamma)}{\Gamma(H \to \gamma\gamma)} \sim 1.7\%,$$
$$\frac{\Gamma(H \to Z\gamma \to \ell\ell\gamma)}{\Gamma(H \to \gamma\gamma)} \sim 2.3\%.$$

The $H \to \gamma^*\gamma \to e\ell\gamma$ decay is distinct from $H \to \gamma\gamma$ followed by a conversion of a photon to an $e^+e^-$ pair in the detector, which can become a background for $H \to \gamma^*\gamma$ if photon conversions are not properly identified. Experimentally, the various contributions shown in Figs. 1 and 2 can be disentangled to some extent. Requirements on $m_{\ell\ell}$ and the transverse momentum ($p_T$) of the photon are used to separate $H \to \gamma^*\gamma$ and $H \to Z\gamma$. Events with final-state radiation are removed by requiring the photon to be isolated from either of the leptons. Contributions from $H \to (J/\psi)\gamma \to \ell\ell\gamma$ and other resonances are identified and rejected or selected based on the value of $m_{\ell\ell}$.

The ATLAS and CMS Collaborations at the CERN LHC have both performed a search for $H \to Z\gamma \to \ell\ell\gamma$ decay with $m_{\ell\ell}$ above 50 GeV [12,13]. As a natural extension of those analyses, the current paper describes the first search for a Higgs boson Dalitz decay, $H \to \gamma^*\gamma$, where the $\gamma^*$ decays into a muon or an electron pair. The search is performed for a Higgs-like particle within the mass range between 120 and 150 GeV. In order to select the...
contribution from the Dalitz decay, we require \( m_{\ell\ell} < 20 \text{ GeV} \). The \( \mu\mu\gamma \) topology is a clean final state with a mass resolution of about 1.6%, as measured from the simulated signal samples. The \( \ell\ell\gamma \) channel is challenging due to the low \( m_{\ell\ell} \) that results in a pair of merged electron showers in the electromagnetic calorimeter (ECAL). Nevertheless, when the merged showers are reconstructed in the ECAL, a mass resolution of 1.8% is achieved. Important backgrounds include the irreducible contributions from the initial- and final-state photon radiation in Drell–Yan production, and Drell–Yan events with additional jets where a jet is misidentified as a photon.

In addition, a search is performed for \( H \to (J/\psi)\gamma \to \mu\mu\gamma \) decay for \( m_H = 125 \text{ GeV} \), which is sensitive to the Higgs boson coupling to charm quark and a promising way to access the couplings of the Higgs boson to the second generation quarks at the LHC. In the SM this decay occurs through two main processes: direct coupling of the Higgs boson to charm (Fig. 2a), and the usual \( t/W \) loop, where the radiated \( \gamma^* \) converts to a \( c\bar{c} \) in a resonant state (Fig. 2b). The two amplitudes interfere destructively and the second one dominates \([6,7]\). For the SM Higgs boson with \( m_H = 125 \text{ GeV} \), the branching fraction is predicted to be \( 2.8 \times 10^{-6} \). A search by the ATLAS Collaboration for this decay is described in Ref. \([14]\).

The results presented in this paper are based on proton–proton collision data recorded in 2012 with the CMS detector at a centre-of-mass energy \( \sqrt{s} = 8 \text{ TeV} \), corresponding to an integrated luminosity of 19.7 fb\(^{-1}\).

Fig. 1. Diagrams contributing to \( H \to \ell\ell\gamma \). The contributions from diagrams (a), (b), and (c) dominate. The final-state radiation of \( H \to \mu\mu \) decay, shown in diagram (d), is important at high dilepton invariant mass. Higher order contributions from diagrams (e), (f) and (g) are negligible.

Fig. 2. Diagrams contributing to \( H \to V\gamma \to \ell\ell\gamma \) decay.

2. CMS detector and trigger

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. \([15]\). The central feature of the CMS apparatus is a superconducting solenoid, 13 m in length and 6 m in diameter, which provides an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, the ECAL, and a hadron calorimeter (HCAL). Charged-particle trajectories are measured by silicon pixel and strip trackers, covering \( 0 \leq \phi \leq 2\pi \) in azimuth and \( |\eta| < 2.5 \) in pseudorapidity. A lead tungstate crystal ECAL surrounds the tracking volume. It is comprised of a barrel region \( |\eta| < 1.48 \) and two endcaps that extend up to \( |\eta| = 3 \). A brass and scintillator HCAL surrounds ECAL and also covers the region \( |\eta| < 3 \). Iron forward calorimeters with quartz fibers, read out by photomultipliers, extend the calorimetric coverage up to \( |\eta| = 5 \). A lead and silicon-strip preshower detector is located in front of the ECAL endcaps. Muons are identified and measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The detector is nearly hermetic, allowing energy balance measurements in the plane transverse to the beam direction.

A two-tier trigger system selects collision events of interest for physics analysis. Two triggers are used in the current analysis. In the muon channel, the trigger requires a single muon and a photon, both with \( p_T \) greater than 22 GeV. In the electron channel the \( \gamma^* \to ee \) process at low dielectron invariant mass mimics a photon at the trigger level. For this reason, a diphoton trigger is used in the electron channel, for \( \gamma + \gamma^* \) final state. The trigger requires a leading (subleading) photon with \( p_T > 26(18) \text{ GeV} \). The diphoton trigger is inefficient for events with high dielectron invariant mass \( (m_{ee} > 2 \text{ GeV}) \) due to the isolation and shower shape requirements. The available dielectron triggers cannot be used to select events with \( 2 < m_{ee} < 20 \text{ GeV} \) because they also require isolation, and the \( p_T \) requirement made on the subleading lepton is too high.
3. Event reconstruction

The photon energy is reconstructed from a sum of signals in the ECAL crystals [16]. The ECAL signals are calibrated and corrected [17], and a multivariate regression technique, developed for the H → γγ analysis [18], is used to determine the final energy of the photon [16]. The neighboring ECAL crystals with energy deposition are combined into clusters, and the collection of clusters that contain the energy of a photon or an electron is called a supercluster. Identification criteria are applied to distinguish photons from jets and electrons. The observables used in the photon identification criteria are: the isolation variables, the ratio of the energy in the HCAL towers behind the supercluster to the electromagnetic energy in the supercluster; the transverse width in ς of the electromagnetic shower; and the number of charged tracks matched to the supercluster. The efficiency of the photon identification is measured using Z → ee data by reconstructing the electron showers as photons, and found to be 80(88%) at a transverse energy > 30(50) GeV and |ς| < 1.44.

Muon candidates are reconstructed in the tracker and identified by the particle-flow global event reconstruction algorithm [19, 20] using hits in the tracker and the muon systems. This approach allows us to maintain a high efficiency independent of the dimuon invariant mass and to reconstruct muons with p_T as low as 4 GeV. Muons from γ* → μμ internal conversions are expected to be isolated from other particles. A cone of size ΔR = √(Δη)² + (Δϕ)² = 0.4 is constructed around the momentum direction of each muon candidate [21]. The relative isolation of the muon is quantified by summing the p_T of all photons, charged and neutral hadrons within this cone, and then dividing by the muon p_T. The resulting quantity, corrected for additional underlying event activity due to pileup events, is required to be less than 0.4 for the leading muon. The isolation requirement rejects misidentified leptons and background arising from hadronic jets. The ΔR(μμ) separation between the two muons is small due to their low invariant mass (as shown in Fig. 3) and high p_T of the γ* in H → γγ decays. Hence, no isolation requirement is applied to the subleading muons as they are already within the isolation cone of the leading muons in most events. Dimuon identification and isolation efficiency of about 80% is obtained.

In the electron channel of the H → γγ → ℓℓγ decay, the two electrons produced in the γ* → ee process are even closer to each other than in the muon channel, since the m_{ℓℓ} is smaller (Fig. 3). Therefore, their energy deposits in the ECAL are merged into one supercluster giving rise to a unique signature. To identify these merged electrons, two tracks associated to the supercluster are required. A Gaussian sum filter (GSF) algorithm is used to reconstruct the electron tracks [22]. The supercluster energy must correspond to p_T > 30 GeV and be located in the ECAL barrel (|ς| < 1.44). The scalar sum p_T^γ + p_T^ℓ of the corresponding two GSF tracks must exceed 44 GeV. Both GSF tracks are required to have no more than one missing hit in the pixel detector in order to reduce the background from photons converting to e^+e^- in the detector material. A multivariate discriminator is trained to separate the γ* → ee objects from jets or single electrons. The input variables for the training include lateral shower shape variables, the median energy density in the event to take into account the pileup dependence, and the kinematic information from the supercluster and tracks. A combined reconstruction and selection efficiency of ~40% is achieved for the signal. For comparison, the efficiency for a single isolated electron with similar p_T is ~88% [23].

4. Simulated samples

The description of the Higgs boson signal used in the search is obtained from simulated events. The samples for the Dalitz signal are produced at leading-order using the MadGraph 5 matrix-element generator [24] with the ANO-HFET model [25], interfaced with PYTHIA 6.426 [26], for the gluon and vector boson fusion processes, and for associated production with a vector boson. Associated production with a tt pair is ignored because of its small contribution. The sample for H → (ℓ/ψ)γ is produced with the PYTHA 8.153 generator [27], and reweighted to simulate 100% polarization of the J/ψ. The parton distribution function (PDF) set used to produce these samples is given by CTEQ6L1 [28]. The SM Higgs boson production cross sections are taken from Ref. [11]. The branching fractions for H → γγ and H → (ℓ/ψ)γ are taken from Ref. [6]. For the SM Higgs boson in the mass range of 120–150 GeV, the H → γγ branching fraction is expected to be between 2.0(4.5) × 10⁻⁵ and 3.3(7.5) × 10⁻⁵ for m_H below 20 GeV. The expected branching ratio for H → (ℓ/ψ)γ is (2.8 ± 0.2) × 10⁻⁶ for m_H = 125 GeV, which is further suppressed due to the J/ψ meson decay to muons, B(J/ψ → μμ) = 0.059.

The simulation aims to include all known effects and the conditions of real data taking in CMS. Some residual differences between the data and simulation are taken into account by reweighting the simulated events with scale factors. Systematic uncertainties are assigned to cover imperfect knowledge of residual differences. Scale factors are implemented to match the distribution of primary vertices, the photon identification and isolation efficiency, and the muon isolation efficiency. No corrections are applied to the muon and electron identification and trigger efficiencies, but an uncertainty is assigned as described in Section 7.

The energy and momentum resolution of muons and photons in simulated events are corrected to match that in data. The energy scale of muons (photons) is corrected to that found in Z → μμ (ee) events. For the electrons, no resolution or scale corrections are applied because of their unique topology, and the absence of a data-driven method to derive those corrections. Therefore, we rely on the simulation of the γ* → ee process and assign uncertainties sufficient to cover any possible discrepancy in the scale and resolution between data and simulation.
Table 1
The expected signal yield and the number of events in data, for an integrated luminosity of 19.7 fb⁻¹. Signal events are presented before and after applying the full selection criteria described in the text. In the (ψγ) sub-category only the (ψγ → μμγ) decay is considered, and the signal yield is a sum of two contributions: H → (ψγ → μμγ) and H → γγ → μμγ, where the dimuon mass distribution is non-resonant.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Signal events before selection m_H = 125 GeV</th>
<th>Signal events after selection m_H = 125 GeV</th>
<th>Number of events in data 120 &lt; m_γγ &lt; 130 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>μμγ</td>
<td>11.9</td>
<td>1.3</td>
<td>151</td>
</tr>
<tr>
<td>eeγ</td>
<td>25.8</td>
<td>1.9</td>
<td>65</td>
</tr>
<tr>
<td>(ψγ → μμγγ)</td>
<td>0.065(ψγ) + 0.32 (non-res.)</td>
<td>0.014(ψγ) + 0.078 (non-res.)</td>
<td>12</td>
</tr>
</tbody>
</table>

5. Event selection

Events are required to pass the muon plus photon trigger in the μμγ final state and the diphoton triggers in the eeeγ final state. The trigger efficiency for signal events after the selection requirements described below is 85% (90%) in the muon (electron) channel, as measured from the simulated samples.

The muons (electrons) are required to be within |η| < 2.4 (1.44), while the photon is required to be within |η| < 1.44. The invariant mass of the (ψγ) system, m_ψγ, is required to satisfy 110 < m_ψγ < 170 GeV. The photon and dilepton momenta both must satisfy p_T > 0.3 m_ψγ requirement, which is optimized for high signal efficiency and background rejection.

On average, there are 21 pp interactions within the same bunch crossing in the 8 TeV data, which result in about 16 collision vertices reconstructed in each event. The vertex with the highest scalar sum of the p_T² of its associated tracks is taken to correspond to the primary interaction vertex. The primary vertex must have the reconstructed longitudinal position (z) within 24 cm of the geometric centre of the detector and the transverse position (x-y) within 2 cm of the beam interaction region. The lepton tracks from γ⁺ → μ⁻ μ⁺ (ee) are required to originate from the primary vertex, and to have transverse and longitudinal impact parameters with respect to that vertex smaller than 2.0 (0.2) mm and 5 (1) mm, respectively.

The muons must be oppositely charged, and have p_T > 23 (4) GeV for the leading (subleading) lepton. The p_T requirement on the leading muon is driven by the trigger threshold, and on the subleading muon by the minimum energy needed to reach the muon system, while maintaining high reconstruction efficiency.

In the electron channel, no additional selection on p_T of the GSF tracks is necessary, beyond those described in Section 3. Finally, in both muon and electron channels, the separation between each lepton and the photon is required to satisfy ΔR > 1 in order to suppress Drell–Yan background events with final-state radiation.

The dilepton invariant mass in the muon channel is required to be less than 20 GeV to reject contributions from pp → γZ and to suppress interference effects from the H → γZ process and the box diagrams shown in Fig. 1. Events with a dimuon mass in the ranges 2.9 < m_μμ < 3.3 GeV and 9.3 < m_μμ < 9.7 GeV are rejected to avoid the (ψ → μμγ) and T → μμγ contamination. In the electron channel the invariant mass, constructed from the two GSF tracks, is required to satisfy m_e < 1.5 GeV. The m_μμ distributions for simulated signal events are shown in Fig. 3 in the muon and electron channels.

In the search for the H → (ψγ) → μμγγ, both p_T² and p_T²(H) > 40 GeV are required, and the events are selected with 2.9 < m_μμ < 3.3 GeV.

The observed yields after the event selection described above are listed in Table 1. In the electron channel, there is also a contribution from the H → γγ process due to unidentified conversions, which is about 15% of the H → γ⁺γ⁻ signal (0.2 events at m_H = 125 GeV). This contribution is considered as a background to H → γ⁺γ⁻, and negligible compared to the continuum background estimated from the fit to data described in the next section.

6. Background and signal modeling

The background is modeled by fitting a polynomial function to the eeeγ mass distributions in data. An unbinned maximum likelihood fit is performed over the range 110 < m_eeγ < 170 GeV. Fig. 4 shows the m_eeγ spectra, which are fitted with polynomial functions of fourth degree. The reduced x² of the fits are 0.5 and 0.7 for the muon and electron channels, respectively. Even though the search is limited to 120 < m_H < 150 GeV, the fits to the m_eeγ spectra are performed over a wider range, giving a better modeling of the background, particularly at the edges of the search range. The degree of the polynomials is chosen following a procedure similar to the one described in Ref. [30]. This procedure ensures that the potential bias due to the background modeling is at least five times smaller than statistical uncertainty.

For the H → (ψγ) search, where only the single Higgs boson mass hypothesis m_H = 125 GeV is investigated, a fit to a polynomial of second degree is performed over the 110–150 GeV mass range (Fig. 5).
The signal model in all three cases is obtained from an unbinned fit to the mass distribution of the corresponding sample of simulated events to a Crystal Ball function \[31\] plus a Gaussian function.

7. Results

The data are used to derive upper limits on the Higgs boson cross section times branching fraction, \(\sigma(pp \rightarrow H)\mathcal{B}(H \rightarrow \gamma^*\gamma \rightarrow \ell\ell\gamma)\) divided by that expected for a SM Higgs boson, for \(m_{\ell\ell} < 20\) GeV. No significant excess above background is observed in the full mass range, \(120 < m_H < 150\) GeV, with a maximum excess of less than two standard deviations. In the electron channel a correction is made to account for the events that are removed by the requirement of \(m_\ell < 1.5\) GeV due to the trigger and reconstruction inefficiencies described above.

The exclusion limits are calculated using the modified frequentist \(\text{CL}_{s}\) method \([32\text{--}36]\). An unbinned evaluation over the full mass range of data is used. The uncertainty in the limit is dominated by the size of the data sample and systematic uncertainties have a small impact.

The systematic uncertainty in the limits results only from the uncertainty in the signal description, as the background is obtained from data and biases in the fitting procedure have been found to be negligible. A summary of the systematic uncertainties is given in Table 2. The uncertainty can be separated into the uncertainty resulting from theoretical predictions and from the uncertainty in detector reconstruction and selection efficiency.

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**Table 2**

Systematic uncertainties affecting the signal.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated luminosity (Ref. [37])</td>
<td>2.6%</td>
</tr>
<tr>
<td>Theoretical uncertainties:</td>
<td></td>
</tr>
<tr>
<td>PDF</td>
<td>2.6--7.5%</td>
</tr>
<tr>
<td>Scale</td>
<td>0.2--7.9%</td>
</tr>
<tr>
<td>(H \rightarrow \gamma^*\gamma \rightarrow \ell\ell\gamma) branching fraction</td>
<td>10%</td>
</tr>
<tr>
<td>Experimental uncertainties:</td>
<td></td>
</tr>
<tr>
<td>Pileup reweighting</td>
<td>0.8%</td>
</tr>
<tr>
<td>Trigger efficiency, (\mu (e)) channel</td>
<td>4(2)/%</td>
</tr>
<tr>
<td>Muon reconstruction efficiency</td>
<td>11%</td>
</tr>
<tr>
<td>Electron reconstruction efficiency</td>
<td>3.5%</td>
</tr>
<tr>
<td>Photon reconstruction efficiency</td>
<td>0.6%</td>
</tr>
<tr>
<td>(m_\ell\gamma) scale, (\mu (e)) channel</td>
<td>0.1 (0.5)%</td>
</tr>
<tr>
<td>(m_\ell\gamma) resolution, (\mu (e)) channel</td>
<td>10 (10)%</td>
</tr>
</tbody>
</table>

The signal model in all three cases is obtained from an unbinned fit to the mass distribution of the corresponding sample of simulated events to a Crystal Ball function \[31\] plus a Gaussian function.
8. Summary

A search for a Higgs boson decay $H \rightarrow \gamma^* \gamma \rightarrow \ell \ell \gamma$ is presented. No excess above the background predictions has been found in the three-body invariant mass range $120 < m_{\ell \ell \gamma} < 150$ GeV. Limits on the Higgs boson production cross section times the $H \rightarrow \gamma^* \gamma \rightarrow \ell \ell \gamma$ branching fraction divided by the SM values have been derived. The observed limit for $m_H = 125$ GeV is about 6.7 times the SM prediction. Limits at 95% CL on $\sigma(pp \rightarrow H) B(H \rightarrow \mu \mu \gamma)$ for a narrow scalar particle without assuming the decay kinematics of a SM Higgs boson, in the muon channel, are shown in Fig. 7. The observed (expected) limit for $m_H = 125$ GeV is 7.3 (5.2$^{+2.2}_{-1.5}$) fb. The total signal efficiency is 24% and almost independent of the dimuon invariant mass. In the electron channel, however, this efficiency depends on the dielectron mass, since it is strongly shaped by the selection. For this reason the corresponding limit in the electron channel is not evaluated.

Additionally, for the SM Higgs boson with $m_H = 125$ GeV, we place an upper limit for a 2.9 $< m_{\ell \ell} < 3.3$ GeV region in the muon channel: $\sigma(pp \rightarrow H) B(H \rightarrow \mu \mu \gamma) < 1.8$ fb, while the expected limit is $1.90 \pm 0.97$ fb. One can interpret this result as an upper limit on $\sigma(pp \rightarrow H) B(H \rightarrow (J/\psi \gamma) \rightarrow \mu \mu \gamma)$ and obtain for the branching fraction, $B(H \rightarrow (J/\psi \gamma) < 1.5 \times 10^{-3}$ at 95% CL, which is about 540 times the prediction in Ref. [6]. The limit on the branching fraction at 90% CL is $B(H \rightarrow (J/\psi \gamma) < 1.2 \times 10^{-3}$. The number of events present in this $m_{\mu \mu \gamma}$ mass window coming from the $H \rightarrow (J/\psi \gamma)$ is large compared to the $H \rightarrow (J/\psi \gamma) \rightarrow \mu \mu \gamma$ (as shown in Table 1). On the other hand it is small compared to the total background, hence it is considered as a part of the background when extracting the limit on $B(H \rightarrow (J/\psi \gamma) \gamma)$.

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